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**STIRLING COMMERCIALIZATION STUDY**  
**FINAL REPORT**

**Volume I**

**by**  
**National Aeronautics and Space Administration**  
**Washington D.C. 20546**

**and**

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## STIRLING ENGINE COMMERCIALIZATION STUDY

### 1.0 EXECUTIVE SUMMARY

The Stirling Commercialization Study was carried out in response to House Report 101-226 accompanying HR1759. The report language claims that "the Stirling engine may eventually contribute to a long-term solution to the Nation's emission problems" and that "supporters of the Stirling engine have proposed a Government and industry cost-sharing demonstration program." "To determine the optimal long-term sponsor for the Stirling engine" the report directed NASA "to participate in an interagency study including the Department of Energy, the EPA and the Air Force, in consultation with other interested agencies, to evaluate potential sponsorship of such a program." The other participating agencies were the Department of Transportation, the United States Army, and the United States Postal Service. The study was to "include the optimal size and scope of the demonstration fleet, a determination of the private sector contribution, and a mechanism for securing such funds." The report encouraged NASA to "consult with the private sector in developing the study plan." The following private sector organizations were consulted:

- Cummins Engine Company, Columbus, Indiana
- Deere & Company, Moline, Illinois
- Ford Motor Company, Dearborn, Michigan
- Gas Research Institute, Chicago, Illinois
- General Motors Research Laboratories, Warren, Michigan
- Hercules Engine Incorporated, Canton, Ohio
- Kennedy Engine Company, Biloxi, Mississippi
- Stirling Thermal Motors Inc., Ann Arbor, Michigan

In 1978 Congress passed the Automotive Propulsion Research and Development Act of 1978 (Title 3, PL95-238). In response the Department of Energy

the Stirling engine as one of two new engines for technology development and selected the NASA Lewis Research Center as project manager for the Automotive Stirling Engine (ASE) Project, which began March 22, 1978. The goals of the DOE ASE program were to develop and verify the technology base necessary to meet the following propulsion system objectives: 1) at least a 30-percent improvement in fuel economy, 2) emission levels that meet or exceed the Federal research standards, 3) the ability to use a broad range of liquid fuels, and 4) suitability for cost-competitive mass production.

The project was carried out utilizing two generations of engines, Mod I ASE and Mod II ASE. The Mod I ASE was intended as a first experimental testbed engine. The Mod II ASE engine was intended, as the proof-of-concept engine, to incorporate all required technologies and to demonstrate the program goals. Mod I ASE's accumulated more than 20,000 hours of operation in laboratories, including more than 3,800 hours and 44,000 miles in vehicle demonstrations. Mod II ASE's have accumulated only 1,700 hours of operation, including about 500 hours and 7,300 miles of operation in a postal delivery van.

The Mod II ASE has successfully demonstrated multifuel operation and good drivability in a vehicle. In addition, the availability of low-cost, high-temperature materials needed for mass production has been established. However, the Mod II ASE in a vehicle has failed to demonstrate the fuel economy or emissions goals of the program. Mod II ASE fuel economy improvements (losses) were inconsistent as demonstrated by the wide range of results (from -5 to +13 percent relative to the spark ignition engine). Emission results were marginal for today's standards and fall far short of projected goals likely to be required by the time the engine could reach the market.

In view of these results the participating agencies and industry organizations contacted have concluded that the proof-of-concept Mod II ASE is not ready for prototype commercial demonstration. The responses have indicated that such a proof-of-concept engine must first demonstrate the basic goals of the program before a commercial demonstration can be justified. As a consequence, none of the Government agencies have indicated a desire to participate in long-term sponsorship of the Mod II ASE commercialization effort at this time.

These determinations, along with the agency and private industry responses, lead to the following findings regarding Stirling engine commercialization:

1. **The Mod II ASE has not achieved a level of performance or value that would interest any Federal agencies or engine/automobile manufactures in a commercial demonstration program.** Neither the Mod II ASE development effort by the engine developer nor the proof-of-concept evaluation conducted with potential users achieved all of their goals, although the proposed engine designs were completed. The fuel economy goals of the program were not met. Although the emissions reduction potential appears to have some promise, it has not been fully determined, nor has the emissions durability of the Mod II ASE been verified. Although the Mod II ASE meets the current level of Federal emissions standards, any new alternative engine such as Stirling must be directed to meet the Federal standard anticipated when the engine will be introduced into the marketplace.

2. **Introducing any new alternative engine directly into the automobile in the near term is highly unlikely because of the large capital investment, the high risk, and the difficulty of predicting manufacturing costs.** Instead, initial application in a niche market at relatively low production quantities may build the confidence and experience needed to support a later mass production decision.



**3. Advancing the program beyond the proof-of-concept phase must involve both the engine and vehicle manufacturer.** The Mod II ASE was intended to offer improved manufacturability and lower cost, the engine and vehicle manufacturers will need to decide what further improvements are necessary for initial market entry.

**4. Commercial demonstration plans must be defined primarily by the engine manufacturer and developer and the user organizations** (both private and Government) and could involve anywhere from 40 to 250 engines.

## 2.0 INTRODUCTION

This study was carried out in response to House Report 101-226 accompanying HR 1759, the NASA Multiyear Authorization Act of 1989. This report language claims that the automotive Stirling engine may eventually contribute to a long-term solution of the Nation's emission problem, and notes that supporters of the automotive Stirling engine have proposed a Government and industry cost-shared demonstration program. As the report directed, NASA participated in an interagency study with the United States Air Force, the Department of Energy, the Environmental Protection Agency, and other interested agencies to determine the potential benefits of such a demonstration program and the optimal long-term sponsor or sponsors if such a demonstration program were to be performed. This study was also to address and to identify the optimal size and scope of a demonstration fleet, the private and public sector contributions, and a mechanism for securing such funds. In addition, the report encouraged NASA to consult with the private sector in developing the study plan. The report language is included as appendix A.

## 2.1 STUDY OBJECTIVES

The following study objectives were defined on the basis of the congressional report language:

1. **Determine the optimal long-term Government sponsor** or sponsors, if any, for automotive Stirling engine commercialization. Agencies to be considered would include the Department of Energy (DOE), the Environmental Protection Agency (EPA), the Department of Transportation (DOT), the National Aeronautics and Space Administration (NASA), the United States Air Force, and the United States Postal Service (USPS).
2. **Determine the optimal size and scope of an automotive Stirling engine demonstration program**, if one appears advisable. The number of engines and vehicles and the demonstration service and length of demonstration should be defined. Past demonstration experience and industry needs should be considered in defining an effective demonstration program.
3. **Determine a mechanism for securing funds**, if a demonstration is performed. This should include the procurement approach, the method of industry contributions, and cost sharing.
4. **Determine the extent of the private sector contribution** that will best promote commercialization. This would include an effective balance of risk, commitment, and ultimate benefits.
5. **Assess the status of Stirling technology** and define the potential of long-term Stirling technologies.

This last objective, although not specifically required under the report language, was added in order to put the possible demonstration program in the appropriate perspective of Stirling technology status both current and future.

## 2.2 BACKGROUND OF STIRLING ENGINE

Stirling engines are classified as either "kinematic" Stirling or "free-piston" Stirling engines. Both configurations operate on the same thermodynamic cycle, called the Stirling cycle.

The kinematic Stirling engine was invented by a Scottish clergyman, the Reverend Robert Stirling in 1816. With the temperature limits of materials available in the 19th century (600 to 800 °F), it could not compete effectively with the steam engine. Except for some water-pumping applications around the turn of the century, it did not receive any significant development attention until the 1940's. Then the N.V. Philips Gloeilampenfabrieken of the Netherlands undertook its development. In the 1970's, first General Motors and then Ford Motor Company conducted Stirling technology efforts under license agreements with N.V. Philips. Their efforts included a Stirling electric vehicle by GM and a Stirling-powered Ford Torino vehicle by Ford. However, both companies ultimately chose not to continue their Stirling work.

United Stirling AB, Malmo, Sweden, an early licensee of N.V. Philips has developed several Stirling engines for a variety of applications, though none has yet been commercially successful. United Stirling was the original source of Stirling technology for the DOE Automotive Stirling Engine Program as discussed later. In recent years United Stirling has been absorbed by Kockums Shipyard, Malmo, Sweden, which is developing Stirling engines for submarine applications.

Stirling Thermal Motors, Ann Arbor, Michigan, another N.V. Philips licensee, was formed in 1979 by Dr. R.J. Meijer, who formerly headed the N.V. Philips Stirling engine program in the Netherlands. STM's early development concentrated on engine designs for stationary and solar applications. During 1989 STM has directed their engine design toward the automotive application.

The free-piston Stirling engine was invented by William Beale at Ohio University in 1962. Up to this point all Stirling engines had been kinematic Stirling engines (see definitions, appendix B). Beale's early work resulted in small-scale fractional horsepower engines that demonstrated the operating principles of the basic free-piston engine.

The free-piston engine has a major advantage over the kinematic engine in that it has only two moving parts (a displacer piston and a power piston), which ride on noncontacting gas bearings and can be hermetically sealed thereby increasing the free-piston Stirling's potential for high reliability and very long life.

Only a few organizations in the United States have been active in developing the free-piston Stirling engine. These include Sunpower, Incorporated, of Athens, Ohio; Mechanical Technology Inc. (MTI) of Latham, New York; and Stirling Technology Company (STC) of Richland, Washington. Recently Cummins Engine Company of Columbus, Indiana, has teamed with Sunpower; and Westinghouse Electric Company of Pittsburgh, Pennsylvania, has teamed with STC in efforts to commercialize the free-piston Stirling. By 1982, a few free-piston engines had been built in the 3- to 4-kilowatt size range. Most recently a space power demonstration engine was designed and built by MTI for NASA. This engine has now delivered more than 22 kilowatts of output power. Today MTI is continuing to develop a space power engine for NASA in the 25- to 50-kilowatt (33- to 67-horsepower) size range. Free-piston Stirling

engines are currently under development for the solar terrestrial power application in sizes ranging from 5 to 25 kilowatts.

## 2.3 ATTRIBUTES OF STIRLING ENGINE

The Stirling engine has a number of attributes that make it attractive, in theory for a variety of engine applications. First, Stirling engines are highly efficient. MTI has claimed that with current technology, automotive Stirling engines should provide fuel economy improvements of at least 30 percent compared with standard internal combustion engines, although the engines MTI has built do not achieve that. Next, Stirling engines have a broad multifuel capability and will operate on essentially any source of heat ranging from nuclear to solar and including liquid, solid, and gaseous fuels. When heat is provided by combustion of a liquid fuel, the Stirling engine's emissions meet the current level of Federal standards without a catalytic converter. This low-emission characteristic stems from the external continuous-combustion system operating at essentially atmospheric pressure. Other attributes due to the external combustion system include reduced noise without a muffler and reduced infrared signature and structural noise. The latter two attributes are of interest to the military. Finally, because Stirling engines require only one igniter, no catalytic converter, and no muffler, they have the potential for very low maintenance costs. Moreover, since the lubricating oil does not come in contact with the products of combustion, there is no need for changing oil or oil filters.

## 2.4 BACKGROUND AND OBJECTIVES OF ASE PROGRAM

In 1975, the Environmental Protection Agency's Automotive Heat Engine Program selected the Stirling engine as one of the promising candidates for achieving national goals for automotive emissions, fuel economy, and multifuel capability. Subsequently, Congress passed the Automotive Propulsion Research

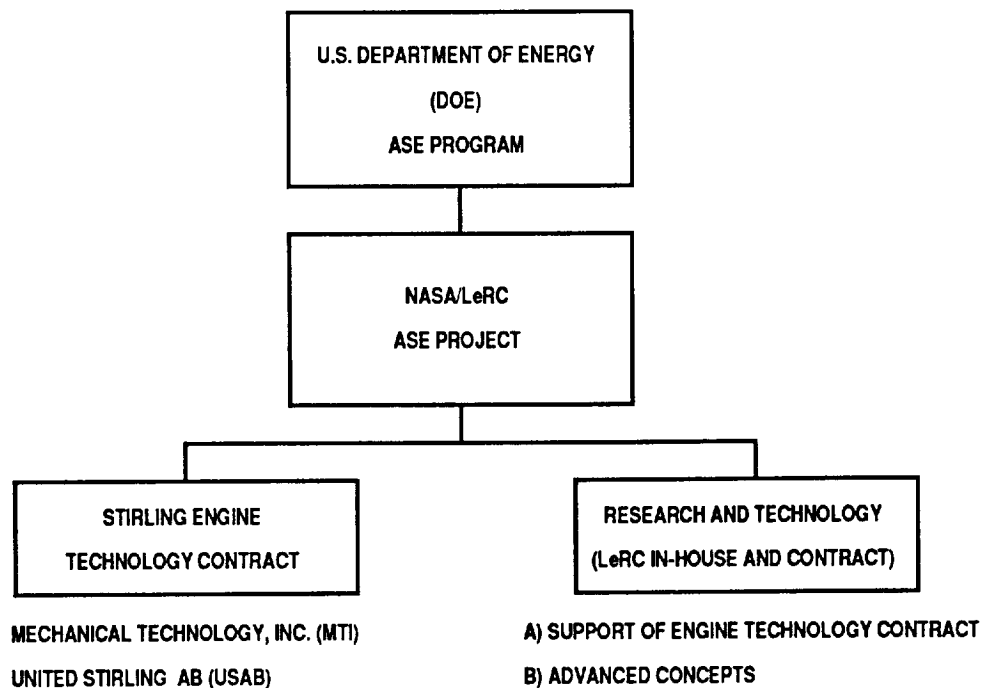
and Development Act of 1978 (Title 3, PL 95-238). The Act specifically directed the Department of Energy (DOE) to "establish and conduct new projects and accelerate existing projects which may contribute to the development of advanced automobile propulsion systems and give priority attention to the development of advanced propulsion systems. With appropriate attention to those advanced propulsion systems which are flexible in the type of fuel used." The Stirling engine and the gas turbine engine were the two "new" alternative engines selected by DOE for technology development in response to PL 95-238.

The NASA Lewis Research Center was selected by the Department of Energy (DOE) as project manager for the Automotive Stirling Engine (ASE) Project. Consistent with PL 95-238 and specific guidelines provided by DOE's Office of Transportation Systems, the goals of the DOE ASE program were to develop and verify the technology base necessary to meet the following propulsion system objectives and to provide confidence in that technology base by verifying the technology in appropriate testbed engines:

1. At least a 30-percent improvement in fuel economy (miles per gallon) over a production vehicle of the same class and performance powered by conventional spark ignition engines (based on equal heating value content of the fuel used).
2. Emission levels that meet or exceed the most stringent Federal research standards; 0.4, 3.4, 0.4, and 0.2 g/mile of hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NO<sub>x</sub>), and particulates, respectively.
3. The ability to use a broad range of liquid fuels derived from crude oil as well as synthetic fuels from coal, oil shale, and other sources.
4. Suitability for cost-competitive mass production.

At the outset of the NASA ASE project certain technologies had to be advanced in order to meet the propulsion system objectives. Specifically, these technology objectives were as follows:

1. To develop high-temperature metal alloys low in content of strategic materials (particularly cobalt).
2. To develop the technology for seals with leakage, friction, and life characteristics suitable for the application.
3. To develop the technology necessary for low-emission combustion systems.



**Figure 1 - DOE program/NASA project organization.**

4. To develop component technologies required to reduce engine cost and weight and to improve engine performance and life in support of the program objectives.

5. To identify and evaluate concepts, not expected to mature by 1987, that may significantly affect engine life, cost, or performance.

The DOE-sponsored, NASA-managed ASE project involving the kinematic Stirling engine began on March 22, 1978. The basic organization of the program is shown in figure 1. The chronology of the DOE ASE program is given in appendix C. The primary engine development effort was conducted by a team consisting of Mechanical Technology Inc. (MTI), Latham, New York, and United Stirling of Sweden (USAB), Malmo, Sweden, under contract to the NASA Lewis Research Center. As the prime contractor, MTI was responsible for overall contract management, development of component and subsystem

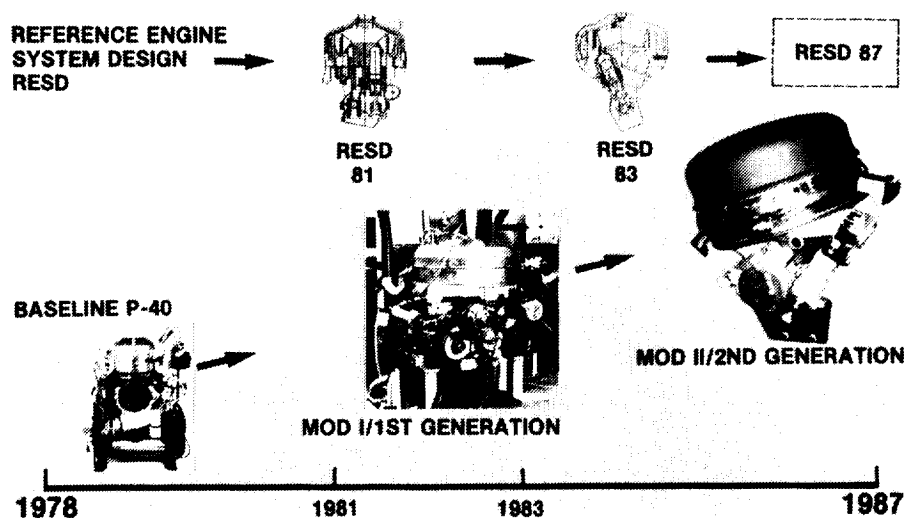


Figure 2 - Engine development contract approach.



technology, and the transfer of European Stirling engine technology to the United States. USAB was responsible for in-engine technology verification and for providing the initial base of Stirling technology to the program.

The technical approach to the project is illustrated in figure 2. The contract effort was focused on a reference engine system design (RESD) intended to represent the best engine that could be designed to meet the program goals by using the technologies reasonably expected to be developed over the life of the program. Two generations of engines were planned in the development of the reference engine. The Mod I engine used technology available early in the program and was a first step toward the RESD. The Mod II engine was then planned to incorporate all of the technologies required for the reference engine design and was to be a proof-of-concept version of the RESD. In 1981, the Mod II engine was deleted from the program and emphasis was placed on demonstrating the RESD technologies in improved versions of the Mod I engine. The Mod II engine was restored to the program in 1984, as a congressional add-on.

In addition to overall project management of the DOE ASE program, NASA Lewis carried out, through both in-house and contracted activities, a number of separate research and technology efforts. These efforts supported the technology verification goal and identified and evaluated more advanced Stirling concepts.

### 3.0 SUMMARY OF TECHNICAL STATUS

This section of the report is directed toward assessing Stirling engine technology status and readiness for a commercial demonstration. Therefore, the ASE portion deals primarily with the vehicle test and evaluation programs, rather than the details of component development and engine dynamometer

tests. The status of other Stirling technologies is presented for completeness and to display some technical options.

### 3.1 STATUS OF ASE PROGRAM

The Mod I ASE (fig. 3) is a four-cylinder double-acting engine with dual crankshafts. It incorporates one canister type of regenerator and cooler per cylinder. As the first engine designed in the program, and in view of high-temperature materials considerations, it was designed for a heater head temperature of 720 °C rather than the 820 °C planned for the RESD. Because the Mod I was designed as a proof-of-concept laboratory testbed engine, it is too large and heavy for passenger car application. The Mod I ASE was installed and tested in light-duty trucks, however.

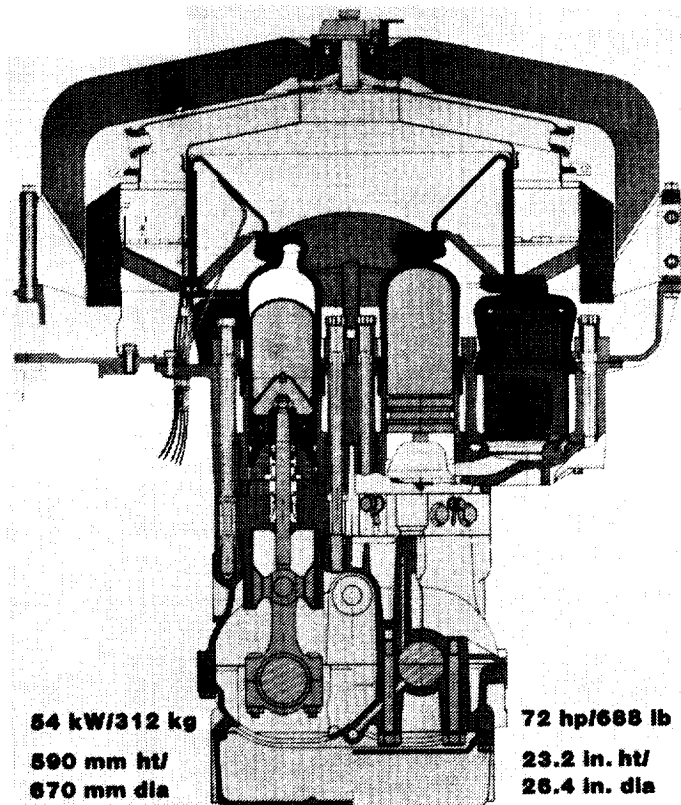


Figure 3 - Mod I ASE.

The Mod II ASE (fig. 4) is considered to be a proof-of-concept engine also and was specifically designed to be installed in a 1985 GM Celebrity automobile with manufacturability as a key consideration (ref. 1). It is a four-cylinder, double-acting engine arranged in a V-configuration with a single crankshaft and was designed to operate at an 820 °C heater head temperature. It incorporates an annular regenerator and cooler wrapped around each cylinder and is substantially smaller and lighter than the Mod I engine (fig. 5).

Seven experimental Mod I engines were produced, including several improved versions. These seven engines have accumulated over 20,000 hours of operation. General Motors Research Laboratories successfully tested one engine in an American Motors Spirit vehicle in the Industry Test and Evaluation Program (ITEP) in 1984. Also in 1984 as part of ITEP, Deere & Co. successfully tested a Mod I engine in one of their test cells. Approximately 4,300 hours and 51,000 miles were accumulated in vehicle demonstration projects with the Mod I and Mod II ASE's throughout the program.

<b>BASELINE PERFORMANCE</b>	
<b>MOD II IN A '85 CELEBRITY</b>	
<b>FUEL ECONOMY</b>	
CITY	33.0 mpg
HIGHWAY	63.2 mpg
COMBINED	42.0 mpg
<b>ACCELERATION</b>	
0 TO 60 mph	13.0 sec
<b>EMISSIONS</b>	
NO <sub>x</sub>	LESS THAN 0.4 g/mi
HC	LESS THAN 0.41 g/mi
CO	LESS THAN 3.4 g/mi
PARTICULATES	LESS THAN 0.2 g/mi
<b>KEY FEATURES</b>	
POWER (MAX)	60 kW (80 hp)
HEIGHT	710 mm (28.0 in)
WIDTH	574 mm (22.6 in)
WEIGHT	203 kg (447.0 lb)

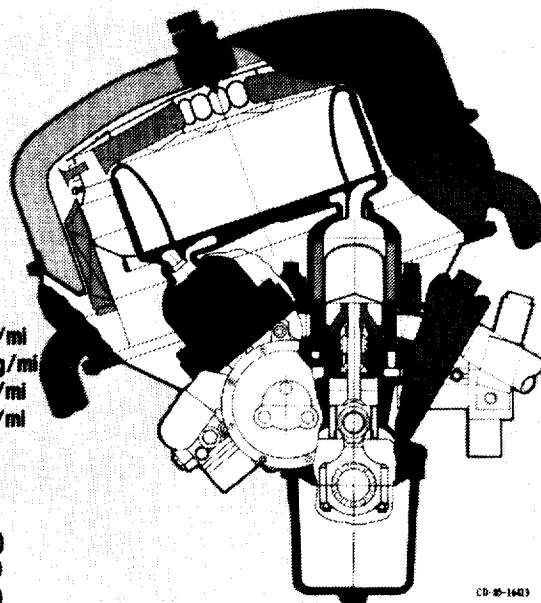


Figure 4 - Mod II ASE.

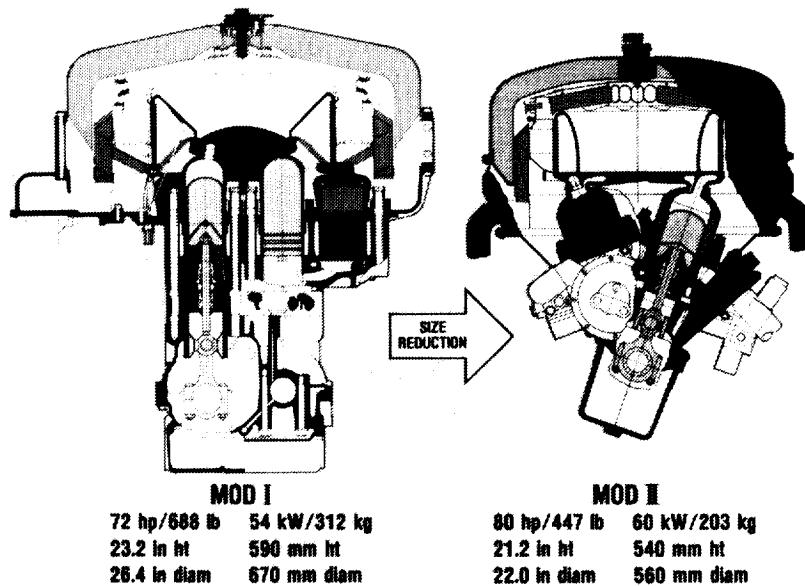


Figure 5 - Comparison of Mod I and Mod II ASE's.

The latter demonstrations were sponsored by the NASA Technology Utilization Office in cooperation with the Department of Energy, the U.S. Air Force, Deere & Co., the American Trucking Associations, and later the United States Postal Service (USPS). Approximately 3,800 hours and 44,000 miles were accumulated in vehicle demonstration activities with Mod I engines throughout the ASE program. The breakdown of these hours is provided in table I.

TABLE I - MOD I ASE VEHICLE EXPERIENCE

	Time, hr	Distance, miles
Lerma automobile	<sup>a</sup> 150	<sup>a</sup> 2,300
Spirit automobile	1,237	13,763
C-30 Van	1,429	8,804
D-150 Pickup truck	<u>~ 1,000</u>	<u>~ 19,000</u>
	~ 3,800	~ 44,000

<sup>a</sup> Estimated

Four Mod II engines were planned to be built and tested. Three engines were actually built and in the final years only two engines could be supported. Mod II ASE's have accumulated a total of 1,700 hours of operation, including about 500 hours and 7,300 miles of operation in a USPS delivery van.

### 3.1.1 Industry Test and Evaluation Program

As part of the DOE/NASA program an Industry Test and Evaluation Program (ITEP) was begun in 1983 to obtain an independent evaluation of the Mod I ASE by automobile and engine manufacturers. The Government offered to loan Mod I engines to industry participants if the participants would conduct the tests and evaluations at their own expense. Two companies (GM and Deere) accepted the Government offer and tested Mod I engines in the summer and fall of 1984, respectively.

General Motors Research Laboratories (GMRL) in Warren, Michigan, requested that the engine be installed in a vehicle to allow a comparison with an existing vehicle system. The engine was installed in a 1981 Spirit and delivered to GM on April 24, 1984. GMRL personnel conducted a three-phase test program that included

1. Emissions and mileage tests using a fuel-based mass system that allowed an assessment of emissions for individual modes of each cycle:
2. Cooling system evaluation in a wind tunnel,
3. Driver evaluation on a test track,

The Mod I ASE installed in the Spirit vehicle successfully completed 54.7 hours of operation and 1,062 miles at the GMRL facilities. Results of these tests

were documented in a GMRL report (ref. 2). The following highlights of these results include quotes from the GMRL report:

1. There were no major hardware failures - reliability "was remarkable during the 54.7 hours of testing."
2. Current Federal emissions standards were met with "a comfortable margin" without a catalytic converter.
3. Acceleration times were considered sluggish by GMRL personnel and "suffered severely at highway speeds."
4. "The engine passed standard cooling tests with ease" (oversized radiator).
5. High-idle fuel flow and the cold-start penalty were identified as major contributors to miles per gallon (mpg) shortfall on the urban cycle.

Emission, mileage, and acceleration results from the GMRL tests are presented in table II.

**TABLE II - EVALUATION OF MOD I ASE BY GENERAL MOTORS (1984)**

Vehicle	Test weight class	Emissions, g/mile			Mileage, mpg			Acceleration, sec	
		HC	CO	NO <sub>x</sub>	Urban	Highway	Combined	0-60	50-70
Chevette	2500	0.30	0.99	0.82	28.4	40.4	32.8	18	13.5
Spirit ASE <sup>a</sup>	2500 <sup>b</sup>	.22	1.92	.49	22.3	40.7	28.0	18.8	19.3
Spirit ASE <sup>a</sup>	3250 <sup>b</sup>	.26	1.87	.59	20.5	34.7	25.1	23.5	21.0
Current emissions standards		0.41	3.40	1.00					

<sup>a</sup> Stirling engine and vehicle system not optimized

<sup>b</sup> Tested on a chassis dynamometer that simulated various test weight classes (TWC)

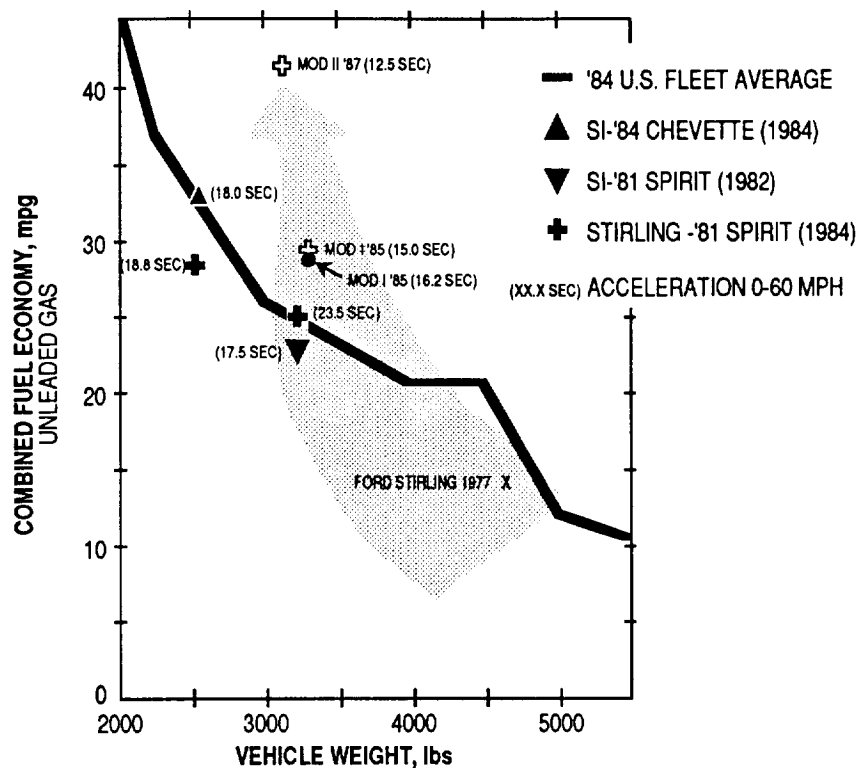


Figure 6 - Comparison of various Stirling powerplants.

Figure 6 places the fuel economy results in perspective. The solid line is the 1984 U.S. fleet average fuel economy. The solid cross symbols are the GMRL test results for the two different test weights run by General Motors. The open cross symbols represent fuel economy projections, first for an improved Mod I in the Spirit vehicle in 1985 and then (at the top of the chart) for the Mod II engine projected for 1987. The solid circle symbol represents actual test data for the Mod I engine in the Spirit in 1985. Because of the changes in the program and the emphasis on the vehicle demonstration aspects, the Mod II engine has never been installed in a passenger car. Thus, a test data point to compare against the Mod II projection is not available. General Motors does not believe Stirling can compete as an automobile engine but wishes to stay informed on Stirling and would be willing to test and evaluate a future Stirling vehicle.

Deere & Company, Moline, Illinois, evaluated a Mod I ASE in a Deere test cell in Waterloo, Iowa, in September and October of 1984. The engine operated for 37 hours with no major hardware failures and was started and operated on gasoline, diesel fuel, and JP-4 without changes to the control or combustor systems. With diesel fuel a significant ignition delay resulted in sooting of the air preheater. Limited noise data were taken although the test cell was not equipped for taking quantitative acoustic data. Qualitative results indicated that the Stirling at full power made no more noise than a normal diesel engine at idle. Tests were run at various heater and cooler temperatures with the predicted effects on power and efficiency. Test results and comparisons with diesel engines are described in detail in the Deere report (ref. 3). On the strength of these test results, Deere elected to participate in the NASA TU Demonstration Project described below as the potential engine manufacturer.

### 3.1.2 NASA Technology Utilization Demonstration Project

The NASA Technology Utilization Demonstration Project was funded by the NASA Technology Utilization (TU) Office and DOE as an adjunct to the ASE program. It was directed toward placing commercial manufacturers and users "on the path to commercialization" of the Mod II ASE. The demonstration project was cofunded by an industry-Government team that included NASA Lewis, the Department of Energy, the Department of the Air Force, Deere & Company, Mechanical Technology Inc., the American Trucking Associations, and later the United States Postal Service. As the prime ASE contractor, MTI was responsible for implementing the NASA TU Demonstration Project. A multiyear, multiphase demonstration program was created by the industry-Government team and is described in detail in reference 4. The primary objectives of the demonstration project were:



1. To obtain early operation and performance data while gaining initial experience in operating the Stirling engine in a typical user environment,
2. To evaluate the Stirling engine under realistic conditions and establish Stirling integrity, reliability, and durability,
3. To accelerate the development of Stirling engines and enable the earliest possible use of the second-generation Mod II ASE. Prior to the TU-sponsored demonstrations, the kinematic Stirling had been virtually a testbed engine and had never been committed to operation in a "real world" environment.

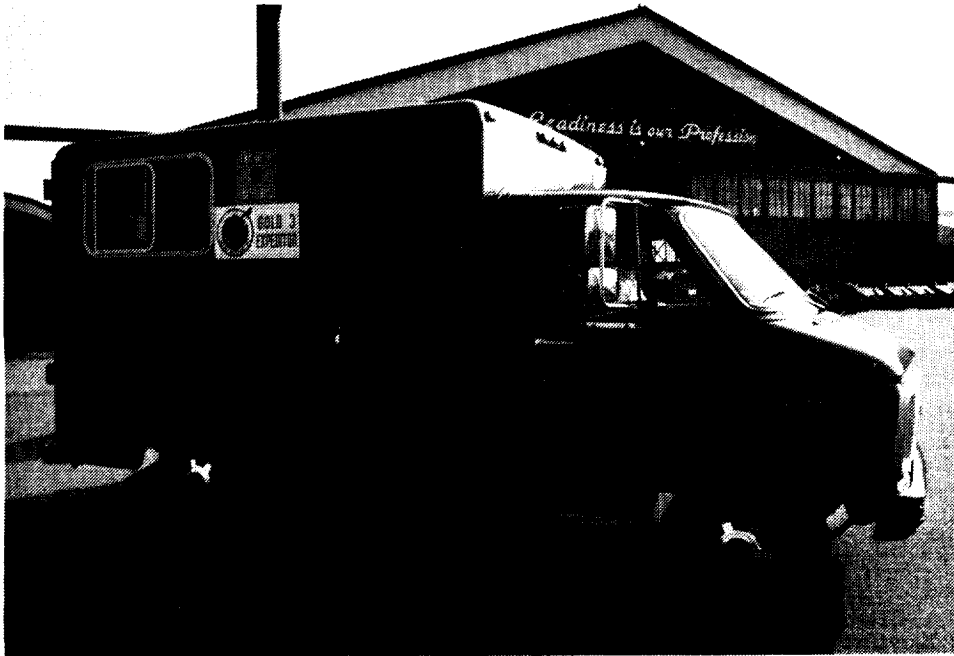
Phase I of the project involved operating a first-generation Mod I Stirling engine for up to 1,000 hours on unleaded gasoline and JP-4 aircraft fuel in an Air Force van under realistic conditions. Langley Air Force Base was chosen because it had an Air Force evaluation team (the Management and Equipment Evaluation Program, or MEEP) and because of the moderate Virginia climate.

Phase II of the project called for up to 1,000 hours of operation with a first-generation engine (Mod I at 775 °C) installed in a van operated in different climate and user conditions. Phase III called for a second-generation engine (Mod II at 820 °C) installed in a van and tested on the basis of the results of phase I and phase II.

For phase I the Air Force provided a 1986 General Motors multistop delivery van (fig. 7) powered by a standard 6.2-liter V8 diesel engine developing 145 horsepower at 3,600 rpm. The vehicle had a curb weight of 6,800 pounds and a maximum gross weight of 8,600 pounds. The 6.2-liter V8 diesel engine was replaced with the 72-horsepower Mod I Stirling engine. The Air Force delivery van was operated by regular Air Force personnel assigned to the 27th Aircraft Maintenance Unit (AMU) of the Tactical Air Command at Langley Air Force Base. The multistop van was designed to transport personnel and light cargo

in a stop-and-go duty cycle. The multistop was used for the "expediter" mission by the 27th AMU, which maintains 15 to 20 fighter aircraft on the Langley flight line. The evaluation was for 10 months, from September 1986 through June 1987 (refs. 5 & 6). More than 1,100 hours and 4,000 miles were successfully logged with the expediter mission.

The Stirling-powered multistop van was operated on unleaded gasoline, JP-4 aircraft fuel, and diesel fuel during the 10-month evaluation period (fig. 8). The multistop successfully towed a variety of support equipment without difficulty. Moreover, Air Force personnel stated that the operation was "not a big deal" and was "better than anticipated." MTI support personnel were available to the Air Force on a daily basis to troubleshoot and to make minor repairs required during the evaluation.



**Figure 7 - Air Force multistop delivery van.**

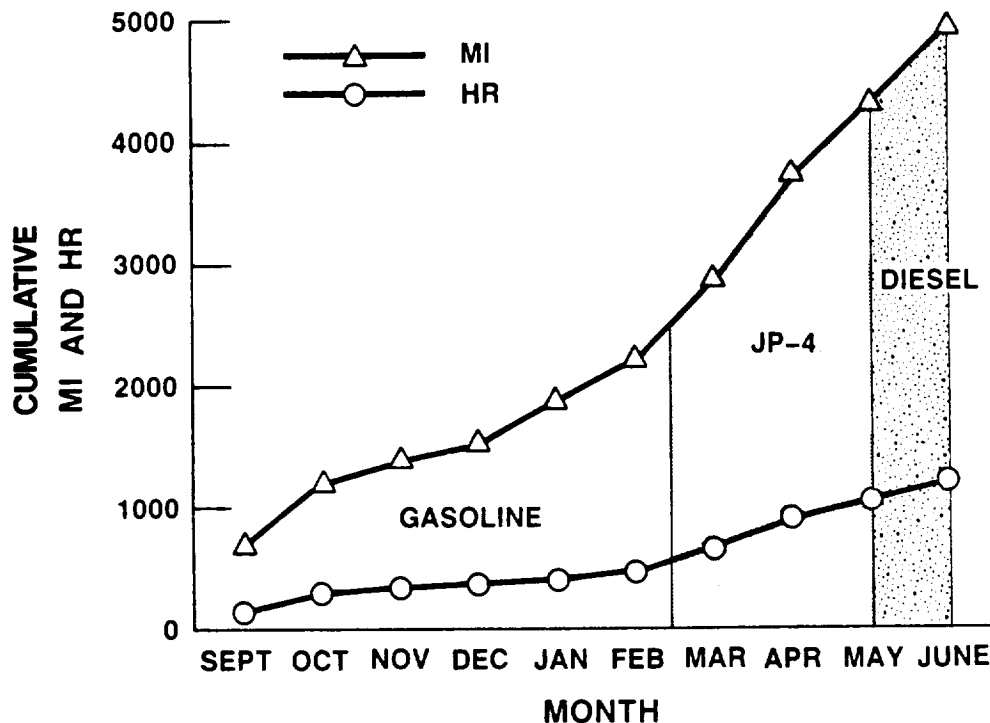


Figure 8 - Operating history of Stirling-powered multistop van.

The multistop van was to be available on a 24-hour basis, as needed by the Air Force. Availability of the van ranged from 55 percent during the early months to an average of 86 percent at the completion of the operational period at Langley. This was considered good for a single-unit demonstration at that stage of development. Vehicle operation was limited to the Langley flight line, where the authorized speed is 15 to 25 mph, and to the base, where the authorized speed is 35 mph. At times the vehicle usage ranged from only a few minutes a day to continuous around-the-clock operation during Air Force readiness exercises. Air Force personnel found the Stirling-powered multistop van to be as reliable as a standard vehicle for the expediter mission.

Following operation at Langley the van was taken to Deere & Company's plant in Moline, Illinois, and placed in service for Deere's local interplant mail delivery, where it accumulated an additional 209 hours of operation.

For the phase II effort a 1987 Dodge D-150 pickup truck was modified for operation with an upgraded Mod I Stirling engine (fig. 9). A 225-cubic-inch (3.7-liter) Slant 6 engine (95 horsepower) was replaced with the Stirling engine. Many of the lessons learned from earlier phase I operations were incorporated in this engine/vehicle build.

The D-150 pickup truck was operated at four Air Force bases for about two months time and 200 operating hours at each base and was driven from base to base on the highway (ref. 7).

The bases and the respective missions were Langley Air Force Base, flight line maintenance mission; Eglin Air Force Base, Ft. Walton Beach, Florida, housing



**Figure 9 - Air Force D-150 pickup truck.**

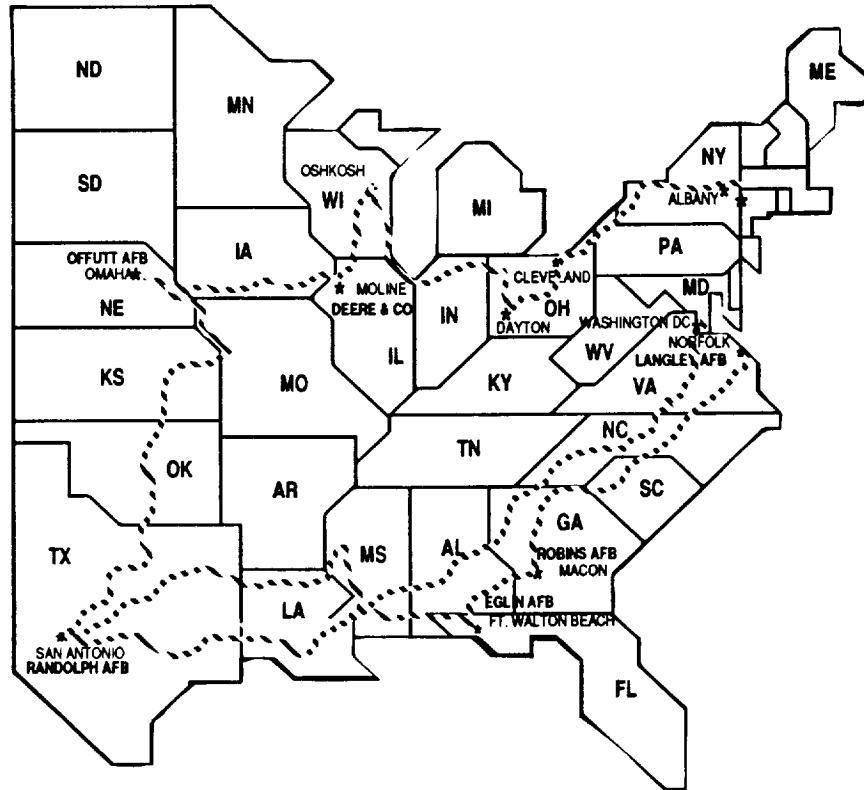


Figure 10 - Major trips made by D-150 pickup truck.

inspection; Randolph Air Force Base, San Antonio, Texas, base taxi service; Offutt Air Force Base, Omaha, Nebraska, civil engineering delivery service. In addition, one side trip was made when the vehicle was driven by Air Force personnel from San Antonio, Texas, to Washington, DC, for congressional hearings in the spring of 1988. In all cases the vehicles were driven by regular Air Force personnel. No drivability problems were encountered either in local urban operation or on the highways.

Figure 10 is a map showing the major trips made by the D-150 pickup truck. While the D-150 was at Eglin Air Force Base, it was tested in the Eglin climatic chamber, where it was subjected to temperatures from 10 to 120 °F. This test consisted of engine startup and warmup operation. Results were encouraging in that no unusual external hydrogen leakage occurred and no oil pressure problems were observed. While at Randolph Air Force base the

D-150 pickup truck was taken to Southwest Research Institute (SwRI), San Antonio, Texas, and tested for emissions and fuel economy. Costs for this testing were shared by Deere & Co. and SwRI.

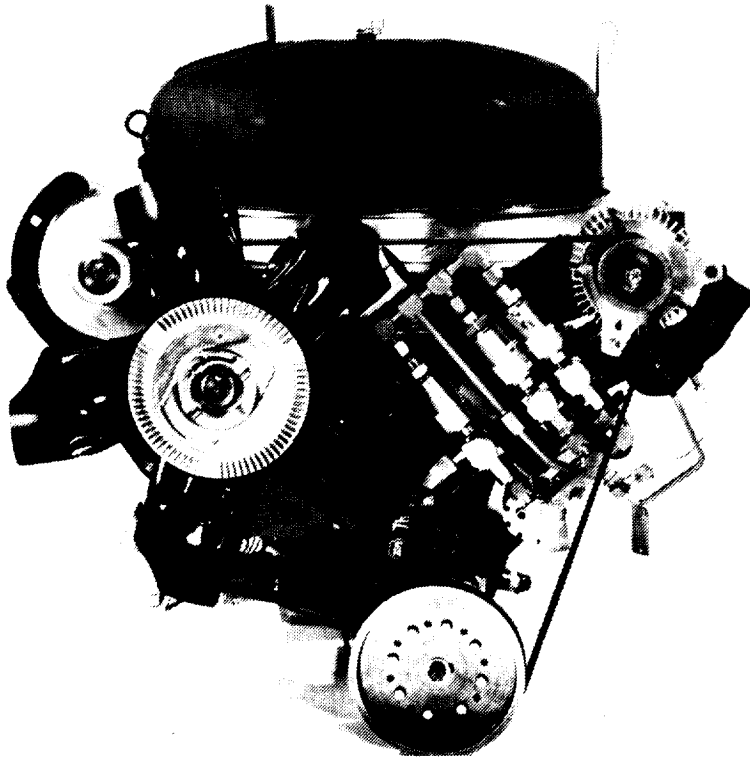
Following the completion of in-service evaluation at the various Air Force bases, MTI made arrangements to have the Mod I D-150 tested by the State of Colorado in Denver. This test was aimed at assessing emissions when operating on 11% methyl tertiary butyl ether (MTBE), an oxygenated fuel designed to reduce CO emissions under high-altitude, low-temperature conditions. Before taking the vehicle to Colorado, MTI returned it to SwRI for some preliminary evaluation and adjustments with the 11% MBTE fuel before the Colorado tests.

In addition MTI took the Mod I D-150 to the U.S. Army Tank Automotive Command, Warren, Michigan, where it was evaluated for infrared signature.

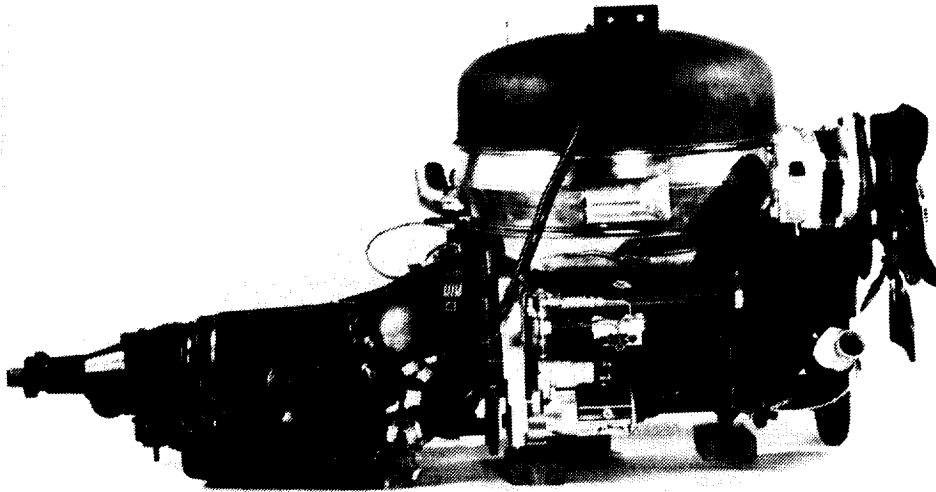
For the phase III effort, a Mod II engine (nominal 73 horsepower) was installed in a 1987 USPS delivery van called a Long Life Vehicle (LLV), shown in figure 11. Figures 12 and 13 show the Mod II engine fully assembled with auxiliaries and transmission ready for installation. In this installation it replaced the 2.5-liter (92 horsepower) "iron duke" engine. This was the same engine that was originally planned to be replaced in the 1985 Celebrity vehicle. The Celebrity installation was dropped from the program in August 1987 because of lack of interest by the automotive companies; however, at the same time, Deere & Co., the potential manufacturer, was participating in the NASA TU Demonstration Project and expressing a strong interest in the light-duty truck/delivery van application. Deere believed this application could be an excellent niche market that might allow initial commercialization of Stirling. It was believed at that time that commercialization of Stirling in a low-volume production, over a period of time, could eventually lead back to a wider scale automotive application.



**Figure 11 - USPS Long Life Vehicle.**



**Figure 12 - Mod II ASE (front view).**



**Figure 13 - Mod II ASE (side view).**

As the DOE program was being closed out, the USPS LLV was sent to the United States Postal Service, Engineering and Development Center, Merrifield, Virginia, for in-service evaluation (ref. 8). USPS conducted engineering tests during October 1989 and then placed the vehicle in actual mail delivery service. This service included combined curblane and park-and-loop mail delivery routes at the Vienna, Virginia, post office during November and December 1989. While providing normal mail delivery service, the Stirling-powered van operated on unleaded gasoline for about 44 hours/276 miles during November and on diesel fuel for about 29 hours/310 miles during December. Operators said they found no difference in drivability of the vehicle compared with the standard-spark-ignition-engine-powered vehicle. However, a number of system-related debugging problems occurred and low-temperature startups again became a problem during the evaluation period. This was not unexpected in view of the lack of debugging activities and cold-start development prior to this evaluation. Post engineering tests were conducted by the USPS at the conclusion of their evaluation period in late December 1989. A total of 123 hours of operation and 1,955 miles were accumulated on the van during the three-month postal service evaluation period.



### 3.1.3 Summary of Results

A variety of operating characteristics of the kinematic Stirling engine were evaluated and assessed during the ASE project and the subsequent TU demonstration effort. This section addresses the various characteristics observed and the status of the technology as it currently exists.

**3.1.3.1 Drivability.** - Early in the DOE program the automotive industry was skeptical of the potential of Stirling to achieve acceptable drivability. All vehicle evaluations, however, from the Spirit tested by GM under the ITEP program through the three vehicles tested in the NASA TU program, exhibited good drivability. The Mod I D-150 pickup truck was driven by a wide variety of personnel under a wide range of operating conditions ranging from flightline service to housing inspection to base taxi. The D-150 pickup truck was also driven on the highway at normal highway speeds when moving between the four Air Force bases and when driven from Texas to Washington, DC. In all cases the D-150 drivability was considered as good as or better than that of the standard vehicles.

**3.1.3.2 Fuel economy.** - Fuel economy results for both Mod I and Mod II ASE engines are included in appendix D. To date, these results are incomplete and inconclusive. Stirling engines have demonstrated fuel economy gains (losses) relative to the standard spark ignition engine of from -5 to +14 percent as determined by standard EPA urban/highway fuel economy tests. The ASE development could be further optimized, but conventional internal combustion engines also continue to improve, perhaps making the 30 percent goal an unreachable moving target.

The Mod II ASE (nominal 80 horsepower) was designed and optimized to replace the 2.5-liter (92 horsepower), four-cylinder "iron duke" engine in the 1985 Celebrity vehicle. Design projections predicted a fuel economy

improvement of 32 percent for the Stirling-powered Celebrity compared with the iron-duke-powered Celebrity. Analysis of the Mod II ASE design in the USPS van resulted in a predicted fuel economy improvement of only 20 percent compared with the spark-ignition-engine-powered van. The predicted reduced fuel economy improvement of only 20 percent resulted from differences in engine/vehicle matching (actual tests showed a 2 to 5 percent loss). In addition, the Mod II ASE installed in the USPS van was somewhat different than the original design. Limited DOE funds in the final stages of the program were directed toward demonstrating the Mod II ASE in the USPS van rather than toward completing the engine performance and technology development and achieving the predicted fuel economy gains.

A high coolant temperature with the Mod II ASE in the USPS van is believed to result from a restricted airflow to the radiator. It should be noted, the USPS would not permit the vehicle appearance to be modified: all cooling air had to enter through the vehicle's normal inlet grill. This was adequate for the spark ignition engine but not for a Stirling, which rejects significantly more waste heat through a larger radiator.

**3.1.3.3 Emissions.** - Emissions results (included in appendix D) are very limited. Basically, these data indicate that the current level of Federal standards can be met without the use of a catalytic converter. However, no emissions durability data have been obtained, and no effort has been made to determine the minimum emissions that Stirling combustion systems might achieve. Review of the limited emissions data shows good emission results for the Mod I engine in the D-150 pickup truck as tested by Southwest Research Institute (ref. 9, 10) and by the State of Colorado (ref. 11). However, the Mod II ASE installed in the USPS LLV displayed emissions significantly different from those obtained in the Mod I ASE test in the D-150. It would appear either that there was something wrong with the Mod II ASE combustion system as tested in the USPS LLV or that the Mod II ASE

combustor is an inherently higher emissions combustor. Several factors could be contributing to these differences. Most significantly, the Mod II combustor is physically smaller than the Mod I so that air/fuel residence time in the combustor is shorter and combustion may not be as complete, thereby resulting in higher emissions. Also the Mod II ASE operated at a higher heater head temperature (820 °C), which may raise combustion temperatures. The higher temperature tends to increase oxides of nitrogen (NO<sub>x</sub>) emissions.

**3.1.3.4 Manufacturing costs.** - Expected manufacturing costs are, of course, a major factor in considering any new alternative engine and are a frequently cited concern by industry in regard to Stirling. An extensive cost study of the Mod II ASE was carried out by Deere & Co. with MTI, as part of the ASE program. In this effort Deere conducted in-depth value analysis and value engineering (VA/VE) to improve manufacturability and lower costs.

Introduction of a number of the VA/VE design modifications aimed at cost reduction, however, could also affect engine performance and therefore would have to be verified in engine testing. This effort was never fully completed and Deere ultimately withdrew from the program. Deere had concluded however, that the engine could be built for a competitive cost for niche markets (e.g., light-duty truck applications) at production rates of about 15,000 units per year.

**3.1.3.5 Other significant results.** - Other significant results included satisfactory operation on a variety of fuels. The Mod I ASE D-150 pickup truck operated well on unleaded gasoline and JP-4 fuels interchangeably. The Mod II ASE USPS van was operated on unleaded gasoline and diesel fuel. To switch from gasoline to diesel only required pressing a button to adjust the control system to the differing fuel characteristics (particularly the air/fuel ratio). This ready capability for operation on a variety of liquid fuels is due to the external combustion system, which operates with low pressure, and continuous combustion and requires no particular octane or cetane rating.

During the NASA project Lewis made a substantial effort to develop and identify low-cost, nonstrategic, high-temperature materials, with low hydrogen permeability, that would allow the Mod II ASE to operate at 820 °C heater head temperatures. This effort was successful. A heater tube material, CG-27, and a heater head casting material, 4G-A1, were identified that met these basic requirements. It is important to note however, that NASA Lewis only addressed material costs, not fabrication costs (machining, brazing, etc.). It should also be noted that limited niche market production (10,000/yr) could drive materials costs up, particularly if there is no other significant use for these materials. A more detailed discussion of the Lewis materials effort is contained in appendix E.

When tested for infrared (IR) signature at the U.S. Army Tank Automotive Command, the Mod I ASE in the D-150 Dodge pickup truck "exhibited much lower IR signature levels during testing," than a conventional V-8 Dodge D-150. The Army indicated that "the low IR signature of the engine would be ideal for applications in light wheeled vehicles for transport of forward observers." The applicability of reduced IR signatures to auxiliary power units and heavy combat vehicles was also suggested (ref. 12). However, the Army did not pursue Stirling engine technology.

The DOE ASE program can claim success in the good drivability demonstrated in the Air Force van, the Air Force D-150 pickup truck, and the USPS delivery van, although it experienced shortfalls in emissions reduction and fuel economy.

**3.1.3.6 Industry concerns.** - At the start of the DOE ASE program industry had indicated a number of specific concerns regarding Stirling and the automobile application. Table III presents these concerns and indicates progress toward resolving them. Cost and vehicle testing were discussed previously.

**TABLE III - INDUSTRY-DEFINED TECHNICAL CONCERNS AND PROGRESS**

<b>Industry concern</b>	<b>Goal</b>	<b>Progress</b>	<b>Comments</b>
Excessive hydrogen leakage	Recharge in 6 months	From one day in Air Force van to 2 weeks in USPS van	Still far from acceptable for commercial use.
Piston ring wear and piston rod seals	3,500 hours	Mod I - 2,000-hour dynamometer endurance test Mod I - 1,429 hours in Air Force van Mod I - 1,204 hours in pickup truck Mod II - 517 hours in USPS van	Promising results with limited statistical base.
Heat rejection	50 °C	Acceptable in Spirit, Air Force van, and pickup truck. Marginal in USPS van (heat rejection and performance modifications to radiator inlet required).	Acceptable in some vehicles but could affect vehicle appearance in some vehicles.
System cost	Competitive with equivalent powerplants	Judged acceptable by Deere when compared with low-volume industrial diesel engines. Heater head costs still a concern.	Selected heater head materials may be too expensive at low production rates if the material application is only for Stirling.
Vehicle operation		ITEP and TU programs showed good drivability.	No longer a concern

### 3.2 STATUS OF ANOTHER STIRLING KINEMATIC CONFIGURATION

Stirling engines are being considered for a variety of stationary and mobile applications ranging from an 8-watt heart-assist pump for medical use in humans up to megawatt size for submarine applications. As previously noted, Stirling engines fall into two basic types, kinematic and free-piston. Kinematic engines use a mechanical device such as a crank or a swashplate to convert reciprocating motion from a piston (or pistons) to rotary motion to power a device such as a generator, a pump, or a vehicle. Free-piston Stirling engines, on the other hand, incorporate an output device such as an electric generator, a hydraulic pump, or a compressor directly into the engine; thus converting reciprocating piston motion directly to useful output power. The following paragraph discusses the status of another kinematic Stirling configuration that may contribute to the application of Stirling engines to the automobile.

The kinematic Stirling engine known as the STM4-120 is being developed by Stirling Thermal Motors, Inc. (STM), Ann Arbor, Michigan. The STM4-120 is a four-cylinder, double-acting engine featuring a variable-stroke power control (see appendix F). The engine was optimized to deliver 25 kilowatts (33 horsepower) at 1,800 rpm, with a maximum power of 40 kilowatts (53 horsepower) at 3,400 rpm. It was originally designed for nonautomotive uses (i.e., generator sets, solar applications, and cogeneration applications) and employed a heat pipe-heater head. During 1989, STM designed a direct-fired heater head for the STM4-120 that they believe would be applicable to city buses and small commuter vehicles. STM has built and done limited testing on four of the heat pipe engines, accumulating about 300 hours of operation. The maximum output delivered to date is about 23 kilowatts (31 horsepower). No efficiency data, however, have been gathered for power levels above 12 kilowatts (16 horsepower). The direct-fired version of the engine has not yet been tested. The STM engines are in the early stages of development and no engine/vehicle system integration studies are under way.

### 3.3 COMMERCIALIZATION READINESS AND TECHNOLOGY STATUS

#### 3.3.1 Commercialization Readiness

From the results presented so far, it is clear that the Mod II ASE has not yet demonstrated the key fuel economy and emission goals of the program. Therefore, it is the opinion of the Government study participants that the subject (Mod II ASE) automotive Stirling engine is not yet ready for a commercial demonstration. To be considered ready for a Government/industry-supported commercial demonstration, a proof-of-concept engine must demonstrate that key criteria critical to the engine's commercial success and its contributing to long-term national energy and environmental goals can be achieved. Key criteria that need to be met in a proof-of-concept evaluation are shown in table IV.

The ability to meet emissions and fuel economy standards should first be demonstrated with a proof-of-concept engine installed either in a vehicle of interest for a niche market (e.g., a light-duty truck) or in a passenger car.

Manufacturability and expected costs should be determined by the manufacturer in an in-depth study of the design and of any modifications required to make it manufacturable at acceptable costs. The proof-of-concept engine need not itself meet the manufacturability requirement, provided that the manufacturer shows how the commercial demonstration version of the engine will comply. Reasonable evidence of durability, especially with regard to emissions, should be demonstrated with the proof-of-concept engine to reduce risk in the commercial demonstration. There is evidence that an ASE can meet the original Federal emissions goals (see pg. 9) of the recently completed 12-year, \$130 million program. However, that program did not provide compelling evidence that future emissions or fuel economy goals could ever be met by the

**TABLE IV - KEY CRITERIA TO BE DEMONSTRATED  
WITH PROOF-OF-CONCEPT ENGINE**

National goals	Industry goals
Environmental: Emissions that meet projected standards <sup>a</sup>  Energy conservation: Fuel economy that meets projected requirements <sup>a</sup> Ability to use a variety of alternative fuels	Manufacturability Cost competitiveness (first cost and maintenance) operating costs such as fuel and maintenance) Ability to meet future emissions standards Ability to use alternative fuels Ability to meet fuel economy requirements

<sup>a</sup>Ten to twenty years in the future.

Mod II ASE. The program has suggested that manufacturability and durability goals can be met, but that has not been fully proven.

The commercial demonstration itself must then be conducted with a prototype engine that incorporates and verifies the design changes required to achieve manufacturability at acceptable costs. Before the actual commercial demonstration can take place, three or four prototype engines should be built and tested thoroughly to verify that the basic fuel economy, emissions, durability, and performance goals are being met. Finally, the number of engines to be built in the prototype demonstration (40 to 250) would depend on the specific market applications being considered and upon the judgment of the entire commercialization team (i.e., the engine manufacturer, commercial and Government users, and the Government agencies involved).



### 3.3.2 Technology Status

No significant technology barriers to the Stirling engine exist when it is examined in light of current standards. However, Stirling needs to be assessed against environmental and energy need standards expected to exist in the future when the engine might see its first years of commercial production. Emissions standards and fuel economy requirements can be expected to change over the next decade or so as conventional engines continue to improve and as emissions standards are modified to meet changing environmental needs.

The primary technology issue at this time is whether or not the Stirling engine (either the kinematic or free-piston configuration) can meet the anticipated emissions standards, say 10 to 20 years in the future. The Stirling apparently can meet the current level of Federal standards although the emissions durability of the engine has not been verified. Further, no attempt has been made in the DOE ASE program to determine the minimum achievable emissions. Thus, Stirling's ability to meet the emissions standards anticipated in the future is unknown.

### 3.3.3 Emissions and Fuel Economy

Current and proposed automotive emissions and corporate average fuel economy (CAFE) standards are traditionally examined separately rather than together as associated standards that influence each other. Current interest in our overall environment has caused an ongoing evaluation by the Government and environmental groups that has resulted in the automotive industry making conventional engines more efficient and cleaner. As a consequence, the baselines in both emissions and CAFE standards and regulations are changing. Also, more stringent emissions regulations are being proposed for all powerplants including truck (light duty and heavy duty) and off-highway and stationary applications. It would be reasonable to expect that in the future all

light trucks, vans, and pickups would have to adhere to the same stringent emissions standards as the passenger car. Furthermore, stricter regulations are being created for unique geographical locations where special conditions exist, such as the ozone formation within confined air basins in California and high carbon monoxide (CO) levels in areas that combine cold weather and high altitude such as Denver, Colorado. Also, additional improvements in fuel economy will reduce emissions of carbon dioxide (CO<sub>2</sub>), the gas that may cause global warming.

Any alternative powerplant proposed for a demonstration program must be designed and evaluated for the emissions and fuel economy standards of the future (not the phase-in procedure currently used for today's production engines) and for the time when it would be introduced into the marketplace. The fuel economy and emissions goals for an alternative powerplant proposed for demonstration today should certainly be directed to the year 2000 and beyond.

#### 4.0 COMMERCIALIZATION ENVIRONMENT

In carrying out this study visits were made to two automobile companies - Ford Motor Company and General Motors Research Laboratories - and several engine companies - Deere & Company, Cummins Engine Company, Hercules Engine Incorporated, and Kennedy Engine Company. An identical list of questions was submitted to each company before the visit to serve as a basis for discussion, and NASA requested that each company provide written responses. The questions and the written responses received are included as appendix G.

## 4.1 INDUSTRY RESPONSES

### 4.1.1 Automobile Companies

The responses from **Ford Motor Company, Dearborn, Michigan, and General Motors Research Laboratories, Warren, Michigan**, were quite similar, reflecting both the same attitudes and the same concerns and issues with Stirling. Both recognized the quiet operation and multifuel capability of Stirling engines. GM also acknowledged the good torque curve for Stirling but feels that this is a minor advantage readily compensated for by the transmission in spark-ignition-powered vehicles. Issues cited by both included the following:

1. **Fuel economy** - Ford believes, on the basis of the ASE test data, that Stirling engine fuel economy is no better than that of the best current spark ignition engines and questions whether it can ever be good enough to justify the investment required for such a new technology. GM concurs based on their evaluation of the 1984 Stirling-powered Spirit vehicle test data, which exhibited poorer fuel economy than the spark-ignition-engine-powered Spirit.
2. **Emissions** - Both companies strongly question the potential for Stirling to reach the 0.2-g/mile NO<sub>x</sub> emission that has been proposed as a standard in the year 2004, indicating that it may be well beyond the capability of the continuous-combustion technology used in Stirling engines.
3. **Packaging** - Both Ford and GM indicated that packaging the Stirling engine, particularly in view of the larger radiator required, might be difficult, particularly with the low hood lines of modern aerodynamic vehicles.

4. Hydrogen containment - Both companies indicated that the current hydrogen recharge interval of approximately 2 weeks was unacceptable for the automobile application. General Motors indicated that hydrogen recharges should be no more frequent than current oil changes.

5. Costs - Both companies expressed concerns over production costs, particularly the cost of the heater head with its high-temperature tubing.

In addition to these issues, General Motors cited concern over the relatively long cold-start times required by Stirling as being unacceptable to the driving public. They also cited the relatively large amount of power required to drive the cooling fan should it be required in extreme operating conditions, such as going up a grade, when the fan might have to cycle on to maintain radiator temperatures. (The Chrysler Corporation was not part of this study because of previous statements by Chrysler that they did not get involved in such advanced technology activities and would instead follow the lead of Ford and GM in pursuing anything as major as a new engine technology.) Neither Ford nor GM chose to respond to our request to define an appropriate demonstration program.

#### 4.1.2 Engine Companies

**4.1.2.1 Deere & Company.** - Deere & Company, Moline, Illinois, submitted a written response including point-by-point answers to the 10 questions that we asked. To summarize briefly our discussions and Deere's written response: Deere had been extremely interested in Stirling and was the key participant (the potential manufacturer) in the NASA TU effort and acted as a subcontractor in conducting the value analysis and value engineering study. As a result of that participation they presented testimony to the Congress explaining in detail what would be needed to commercialize the engine - mainly to conduct a commercial-based field test of a statistically significant

number of prototype engines in the hands of potential buyers. They estimated that a total of \$85 million would be required for the project, with \$20 million to be provided by the Government primarily to support the commercial demonstration program. When Federal support was not forthcoming, Deere dropped the project.

**4.1.2.2 Cummins Engine Company.** - The Cummins Engine Company, Columbus, Indiana, is unique in the United States as the only major U.S. engine manufacturer pursuing Stirling engines for commercial application. Cummins is currently conducting two Stirling engine programs for solar power application. In both cases these are free-piston Stirling engines with electric power output. The first of these is a 5-kilowatt solar-powered, free-piston Stirling conversion system. This activity is privately funded by the Cummins Engine Company. The solar-dish Stirling system has already completed initial proof-of-concept solar-powered tests. The second program is for a 25-kilowatt solar-powered free-piston Stirling engine. This is a cost-shared program funded by DOE and Cummins Engine Company through NASA Lewis serving as the project manager. This DOE/NASA program is currently in the preliminary design stage; neither engine is directly applicable for automotive use. The Cummin's response to our questions must be reviewed in light of their free-piston Stirling engine activities. Highlights of their response follow: Fewer total parts and fewer moving parts along with the reduction or elimination of oil changes leads to the potential for low maintenance, longer life, and increased service intervals with free-piston Stirling engines. Free-piston Stirling technology, however, is in its infancy and requires substantial development. Among key disadvantages are that the free-piston is an infant technology, that Stirling engines require substantially larger waste heat exchangers than conventional engines, and that production costs at this stage are essentially unknown.

**4.1.2.3 Hercules Engine Incorporated.** - MTI has stated that Hercules Engine Inc., Canton, Ohio, would be their engine manufacturer in their proposed

Stirling commercialization efforts. In our discussions with Hercules they indicated that they were prepared to produce the Stirling engine but they would provide no Hercules funds to redesign the engine for production and manufacture. Hercules assessed the kinematic drive system of the Mod II ASE as conventional but was concerned with tight tolerances and unconventional components in the top portion of the engine. Hercules credited the Stirling with having a huge advantage in being "able to burn anything." They believe any new technology engine must either be cheaper, much more fuel efficient, or have much lower emissions. Hercules sees the need for a \$4 to \$5 million effort to redesign the Mod II ASE for production and manufacture, followed by a \$10 to \$15 million cost for tooling to produce 30 to 40 thousand engines per year. Hercules is concerned that the Stirling may be too costly since industrial engines sell at \$1,200 to \$1,300. Hercules gave a strong endorsement to natural-gas spark ignition engines, which it believes will eventually replace diesel engines in heavy-duty applications. No written response has been received from Hercules at this time.

**4.1.2.4 Kennedy Engine Company.** - Kennedy Engine Company, Biloxi, Mississippi, expressed a very strong interest in Stirling engines. They believe that there may be significant advantages in emissions, multifuel capability, and oil disposal, since oil changes can be reduced or eliminated. Their primary concern was their inability to obtain a Mod II ASE from MTI for evaluation. They have identified several niche markets for stationary applications that they believe Stirling can fill but suggested that more detailed marketing studies are needed. They contemplate initial Stirling applications for a 125- to 150-kilowatt Stirling engine in generator sets, cogeneration, heat recovery, marine uses, agriculture, and irrigation. At this time the Kennedy Engine Company is an engine remanufacturer, not a manufacturer. Nonetheless, they believe that they could manufacture engines by purchasing parts from suppliers and assembling and testing the engines themselves.

### 4.1.3 Gas Research Institute

The Gas Research Institute (GRI), Chicago, Illinois, has been supporting the development of stationary (nonautomotive) natural-gas-fired Stirling engines (with some DOE funding) since 1980 in recognition of Stirling's potential for lower emissions and less maintenance than conventional engines. They have invested over \$25 million to develop a variety of stationary, gas-fired kinematic and free-piston Stirling engines. Attempts at commercialization have been unsuccessful. They point out the difficulty for Stirling to compete in low-production stationary markets with conventional engines being produced on a mass production basis. However, they see the long-term potential for the eventual commercial success of stationary Stirling. Thus, GRI plans to continue funding Stirling, although at a lower level, in order to assess worldwide Stirling development and to pursue a technology base program aimed at solving the technical problems that hinder commercialization.

## 4.2 COMMERCIAL DEMONSTRATION NEEDS

### 4.2.1 Demonstration Goals

The industry has suggested that the primary goal of a commercial demonstration would be to provide sufficient information for engine manufacturers and users to make an informed investment decision on proceeding to initial production. Specific objectives of a demonstration would include

1. Determine in a real user environment if the alternative engine meets the basic goals of performance, life, reliability, durability, emissions, and fuel economy.

2. Determine the advantages and disadvantages of the Stirling engine relative to the standard engine for that application.
3. Identify and resolve any new problems revealed in the demonstration.
4. Determine the degree of user acceptance of the Stirling engine in that application.

#### 4.2.2 Definition of Commercial Demonstration

Both automobile companies interviewed (Ford and General Motors) declined to respond to our request for input in this area. Written inputs were received from Cummins, Kennedy, GRI, and Deere, as well as several Government agencies. They state that about 40 to 250 engines would need to be manufactured and installed in vehicles and evaluated in "real world" environments. Additional engines would be needed for life and durability testing and continued component and subsystem performance development. Such a demonstration effort must be carried out in a relatively controlled environment with trained, dedicated personnel to carry out the maintenance activities. The following paragraph from the DOE Electric and Hybrid Propulsion Division's letter (see appendix H for agency responses) distinguishes between a market demonstration, as was carried out in the electric vehicle program, and a technology demonstration as has been suggested for Stirling.

It is important to distinguish that the electric vehicle demonstration was a market demonstration. That is, its goal was to effectively bootstrap an entire industry into existence. In order to achieve that goal, it included all phases of a prototype industry, including manufacturing, marketing, sales, and service. The goal also dictated a fairly large demonstration and well over 1,000 vehicles were involved. By contrast, for the Stirling engine, a more modest technology demonstration may be more appropriate. A technology demonstration involves about 50 to 100 vehicles. These vehicles are usually identical and



concentrated in a small number of fleets, so that maintenance activities can be conducted by properly trained full time personnel. The vehicles can be assigned to different users to evaluate user reactions. The technology demonstration concentrates on an evaluation of vehicle and subsystem performance, reliability, and cost in a semi-controlled environment. It does not attempt to create a prototype industry or to simulate actual free market conditions. The vehicles are assigned to trained personnel and subjected to periodic service and maintenance procedures to assure reliable operation.

## 4.3 BUSINESS CONSIDERATIONS

### 4.3.1 Risk Reduction

Industry comments suggest the major overriding business consideration required to put an alternative engine such as Stirling into production is the very high risk involved. Factors contributing to this high risk include

1. Ability to meet performance goals
2. In-service life, reliability, and durability
3. User acceptance
4. New mass production manufacturing requirements
5. Production costs
6. Maintenance costs
7. Warranty liabilities

This very high risk combined with the very high cost of tooling up for mass production of an alternative engine make it highly unlikely that such a new engine would ever be introduced directly into the high-volume automobile production market. Instead the engine should first be commercialized in limited niche markets in small quantities (of the order of a few thousand per year) where initial tooling costs should be more reasonable. Even then, in these niche markets the risks could still be too high for an engine manufacturer to commit to full production.

#### 4.3.2 Government and Industry Cost Sharing

In addressing the questions of funding and Government and industry cost sharing for a commercial demonstration, it seems appropriate to assess the potential benefits of any alternative engine technology and to whom these benefits would accrue. The DOE ASE program has been aimed at two basic goals - fuel economy and emissions. These are national goals whose benefits would accrue to the general public. The primary corporate benefit is an improved ability to meet future emissions and fuel economy standards.

If a new alternative engine technology shows sufficient potential for meeting key national goals, it might be appropriate that Government funding be provided to help reduce the risk sufficiently so that a manufacturer could arrive at an informed decision and proceed to production. At the same time industry's cost share should reflect a reasonable balance of risk, corporate commitment, and potential corporate benefits (profits and ability to maintain market share in the face of more stringent regulations).

## 5.0 FEDERAL PARTICIPATION AND SPONSORSHIP

Although all the involved Government agencies were cooperative in contributing to this report, none have indicated the desire to participate in long-term sponsorship of a Mod II ASE engine commercialization effort. (See individual agency responses in appendix H.) DOE's Office of Transportation Systems states that the ASE technology and the information "are available for industry's use in any further commercial demonstration activities" and "commercialization efforts focused on demonstrations with potential customers . . . should be supported solely by the industry."

## 6.0 FINDINGS

The following findings are offered regarding the Mod II ASE developed under DOE sponsorship:

1. **The Mod II ASE has not achieved a level of performance or value that would interest any Federal agencies or engine/automobile manufacturers in a commercial demonstration program.** Neither the Mod II ASE development effort by the engine developer nor the proof-of-concept evaluation conducted with potential users achieved all of their goals, although the proposed engine designs were completed. The fuel economy goals of the program were not met. Although the emissions reduction potential appears to have some promise, it has not been fully determined, nor has the emissions durability of the Mod II ASE been verified. Although the Mod II ASE meets the current level of Federal emissions standards, any new alternative engine such as Stirling must be directed to meet the Federal standard anticipated when the engine will be introduced into the marketplace.

**2. Introducing any new alternative engine directly into the automobile in the near term is highly unlikely because of the large capital investment, the high risk, and the difficulty of predicting manufacturing costs.** Instead, initial application in a niche market at relatively low production quantities may build the confidence and experience needed to support a later mass production decision.

**3. Advancing the program beyond the proof-of-concept phase must involve the engine and vehicle manufacturer.** The Mod II ASE was intended to offer improved manufacturability and lower cost, the engine and vehicle manufacturers will need to decide what further improvements are necessary for initial market entry.

**4. Commercial demonstration plans must be defined primarily by the engine manufacturer and developer and the user organizations** (both private and Government) and could involve anywhere from 40 to 250 engines.

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